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THE FIRST THREE YOCTOSECONDS OF RELATIVISTIC HEAVY-ION COLLISIONS* **

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The recent results of the hydrodynamic calculations describing consistently one- and two-particle observables in relativistic heavy-ion collisions suggest that interesting phenomena may take place at the very early stages of the collisions. Firstly, the successful hydrodynamic fits indicate that the initial conditions for the hydrodynamic equations may differ from those obtained from the Glauber model. This may hint to yet unrecognized mechanisms of the particle production and thermalization which are responsible for such modified initial conditions. Secondly, the thermalization processes may be preceded by the free-streaming stage. It is also plausible, that the full three-dimensional hydrodynamic expansion is preceded by the purely transverse, two-dimensional hydrodynamic evolution. Such observations emphasize the importance of the proper matching between the microscopic models of early stages and the hydrodynamic evolution. In this respect, physics of the first 1 fm/c or, equivalently, of the first three yoctoseconds becomes an exciting subject of present and future investigations.

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1. There exists a well known problem of the consistent hydrodynamic description of one- and two-particle observables measured in the relativistic heavy-ion collisions [1]. The so called RHIC HBT puzzle [1–4] refers to the problem of a simultaneous description of the hadronic transverse-momentum spectra, the elliptic flow v_2, and the Hanbury-Brown–Twiss (HBT) interferometry data [5–9].

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Our recent hydrodynamic calculations indicate that the uniform description of the RHIC heavy-ion data may be obtained with the modified Gaussian initial conditions [10]. It has been also found that the successful description of the data may be achieved within the scenario where the initial free streaming of partons is followed by the sudden equilibration and transition into the hydrodynamic regime [11]. There exist also calculations which suggest that the good description of the data may be obtained within the framework of the transverse hydrodynamics [12]. In this approach one assumes that only transverse degrees of freedom are thermalized. All these findings suggest that interesting new phenomena may take place at the very early stages of the relativistic heavy-ion collisions.

2. In the typical hydrodynamic approach the ratio of the pionic HBT radii $R_{\rm out}/R_{\rm side}$ reaches the values around 1.5, while the experimental results approach unity (for the transverse momentum of the pair $k_\perp \sim 0.5$ GeV). The experimental results indicate the presence of the strong transverse flow and the relatively short emission time. This interpretation indicates that the equation of state cannot have a distinct soft point. Indeed, the use of the semi-hard equation of state worked out in Ref. [13], based on the simple interpolation between the hadron-gas model and the lattice data, helps to reduce the model values of the ratio $R_{\rm out}/R_{\rm side}$ to 1.20–1.25 [14], see also Refs. [15, 16].

Another important ingredient in the modeling of the correlation functions is the single freeze-out scenario that allows for the unified description of the chemical and kinetic freeze-out [18]. The use of this approach shortens the emission time and helps to reproduce $R_{\rm out}/R_{\rm side}$. We note that in Refs. [10, 11, 14] the hadron emission at freeze-out is modeled with the Monte Carlo code `THERMINATOR` [19]. This allows the implementation of the two-particle method of the calculation of the correlation functions with or without the Coulomb corrections.

In Ref. [10], we showed that an *even better* description of the data may be achieved if the typical initial conditions, obtained from the optical Glauber model, are replaced by the Gaussian energy-density profiles in the transverse plane that have the following form

$$n(x,y) = \exp\left(-\frac{x^2}{2a^2} - \frac{y^2}{2b^2}\right) . \tag{1}$$

Here x and y are the transverse coordinates while a and b are the width parameters such that $\langle x^2 \rangle = a^2$ and $\langle y^2 \rangle = b^2$. We note that the Gaussian profiles originate from the Glauber model — they are Gaussian fits to the source distribution determined by the Monte Carlo version of the Glauber model [20]. The main difference between the standard and Gaussian profiles is that the Gaussian distribution is steeper in the central part. This shape implies the faster development of the transverse flow. Since the magnitude of the transverse flow at freeze-out is constrained by the experimental data, the faster development of the flow means that the evolution is faster and the duration of the emission process is shorter. This is once again the requested feature which helps to reproduce correctly the ratio $R_{\mathrm{out}}/R_{\mathrm{side}}$ — see Fig. 1.

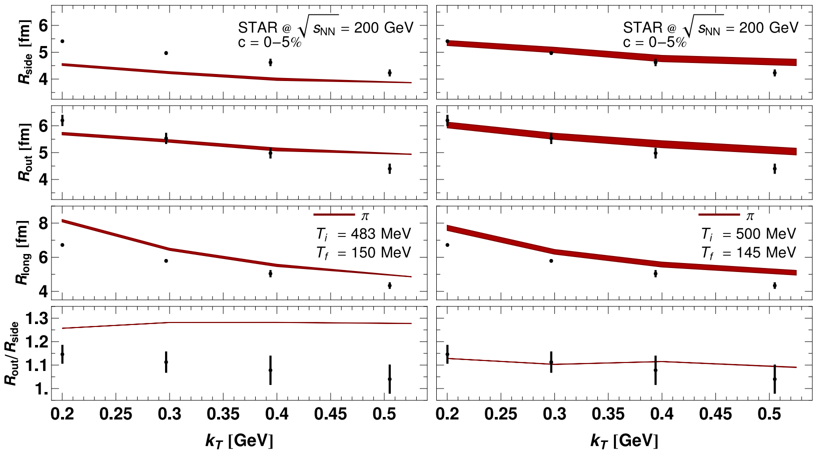

Fig. 1. The pionic HBT radii R_{side}, R_{out}, R_{long}, and the ratio $R_{\mathrm{out}}/R_{\mathrm{side}}$ for central collisions, shown as the functions of the average momentum of the pair and compared to the RHIC Au+Au data [21]. The left part illustrates our best results obtained with the standard Glauber initial conditions [14], while the right part illustrates the results obtained with the Gaussian initial conditions [10].

3. The results shown in Fig. 1 were obtained from the boost-invariant hydrodynamic evolution with the starting proper time $\tau_0 = 0.25$ fm. In the more recent work [11], we showed that the hydrodynamic evolution may start later, for example at $\tau = 1$ fm, and the description of the data is not spoiled. This is possible, however, if the hydrodynamic evolution is preceded by the free-streaming stage of partons, in the proper time interval $0.25\,\mathrm{fm} \leq \tau \leq 1\,\mathrm{fm}$, which suddenly equilibrate at $\tau = 1$ fm. In such a scenario (free-streaming + sudden equilibration, FS+SE, see [22, 23]), the very fast transition from the free-streaming stage to the hydrodynamic regime is described with the help of the Landau matching conditions applied to the energy-momentum tensor. Fig. 2 illustrates that the results obtained in the case when the hydrodynamic evolution starts at $\tau_0 = 0.25$ fm are practically indistinguishable from the results obtained within the FS+SE scenario. This observation suggests that the consistent description of the soft physics at RHIC might be achieved in the approach where the thermalization and the formation of the transverse flow happens gradually [24].

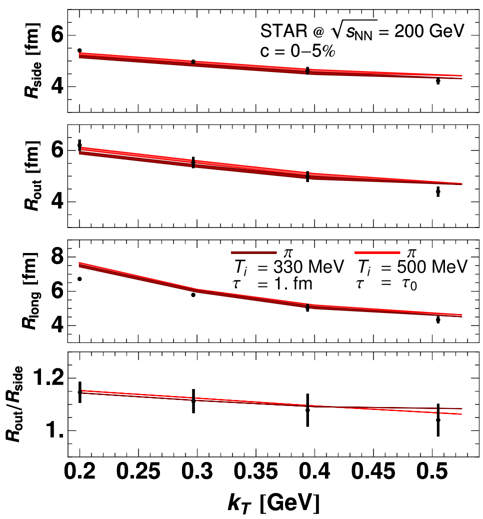

Fig. 2. The pion HBT radii $R_{\rm side}$, $R_{\rm out}$, $R_{\rm long}$, and the ratio $R_{\rm out}/R_{\rm side}$ for central collisions. The darker (lighter) lines describe the results with (without) FS+SE. The data from [21].

4. As shown in Ref. [11], the free-streaming stage leads naturally to the energy-momentum tensor which smoothly matches to the energy momentum tensor of the transverse hydrodynamics. This is so because in the two cases the longitudinal pressure vanishes. The idea of the initial purely transverse hydrodynamic expansion was studied recently in [12] and it was shown to be compatible with the data describing the transverse momentum spectra and the elliptic flow. The inclusion of the isotropization into this description allows also for the description of the pionic HBT data [25]. The results of those studies indicate again that the concept of the gradual thermalization may be compatible with the data.

5. By fitting the hydrodynamic output to one- and two-particle observables we learn about the initial conditions. Those, in turn, should follow from the microscopic calculations describing the early stages, for example from the Color Glass Condensate [26]. The proper matching between such macro and micro approaches remains a challenge. In this context, the investigations of the processes taking place in the first three yoctoseconds remain fascinating and crucial for our complete understanding of heavy-ion collisions.

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